Forces and Atoms: The World of the Physicist*

By KARL K. DARROW

ONE of the signs whereby a pbysicist may be known is a fondness for putting dots upon blackboards. This is not an irrational hahit, but a symbolic practice. It is a symhol of his manner of regarding the world as a multitude incredibly enormous of particles incredibly small. Tbe dots stand for tbe particles, and the hare regions of the blackhoard for the empty spaces between them. The habit has not indeed been universal. Many a thinker has preferred to consider the world as a continuum, a solid or jelly or fluid; and we shall see tbat this alternative has always been very near in the background, even when the "atomists" were at their most triumphant. Let me however defer this other idea, and derive as much as possible from the notion of particles in a void.

But when the dots are set down on the otherwise clean board with regions of black emptiness between, the story is far from completed. It is, in fact, only begun, for the major part is yet to be written: the account of the forces among tbe particles. Tbough these last be separated from each other by spaces apparently empty, yet they are not unconscious of each other, for eacb of them is subject to a force—the resultant of many forces, due to all rest.

One might attach an arrow to each dot, to signify the strengtb and the direction of the force which acts upon it. One might draw wandering curves all over tbe board, to intimate at every point the direction and strength of the force which a particle would feel, were it to he at tbat point. This is accepted practice, hut it would be worth the doing only if our assumptions and our ambitions were much more specific than for the present they are. Perbaps at least the blackhoard should be smeared with a uniform coating of chalk, to signify that a particle in space is not left entirely to itself, but feels the influence of the others. Among our not-so-distant ancestors there seems to have been a psychological need for a gesture of the sort; they talked ahout space as though it were filled with a "medium" or "aether", because it seemed wrong to them to say that space is empty if the particles which wander in it are subject to forces. Our generation has nearly lost the need, whether of an aether to occupy actual space or of a

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smear of chalk to symbolize it on the blackboard. Let us say that space is empty and leave the blackboard black between the dots, without deeming ourselves deprived of the right of saying that the particles exert and suffer forces on and from one another.

What is there to be said about the forces? A very great deal! for most of theoretical physics is made up of beliefs or ideas about the forces, augmented by the mathematical operations—very hard and very long-winded, in far too many cases—required for making the ideas really useful. So great a programme is indicated by that sentence, that I am wasting words in adding that it will not be fulfilled in one or two lectures, nor in the whole of the course. Only the most general of statements can be made in what follows. Of these I lay down at once the first, which is negative and self-evident:

The forces cannot be purely repulsive. For if they were, all of the particles would rush off into the uttermost depths of space, and we should have no model at all for a universe which, with all its faults, does manage at least to stick together.

Therefore there must be attractive forces, and these by and large must overpower the repulsive ones, if any such there be.

But need there be any repulsive forces at all? (Let the sophisticated reader now forget for a little that there are electrical forces which are repulsive, so that he may enquire with an open mind as to whether such could be avoided.) At first, it may not seem so; and one may invoke the great authority of Newton, who is often thought to have contented himself with assigning to all bodies the power of attracting one another with the force of gravity. He did not so content himself, and we shall learn this shortly. For the moment, let it be remembered that forces of attraction unopposed would tend to draw all of the particles of the universe into a single compact clump. If the volume of each particle were infinitely small, so also would be that of the ultimate clump; if the volume of each particle were irreducible below a certain minimum—but we shall ere long find what *that* idea can involve us in! Briefly, there must be something to oppose the attractive forces. To call this something by the name of "force", or even to call it by any single name, would be to limit it unduly. So to the second general statement I give the form:

There must be attractive forces, but there must also be antagonists to them.

If someone wanted a particular problem of the theory of physics identified to him as the profoundest, the problem of these antagonists might well be selected as such.

There is indeed one famed and spectacular case, which makes one antagonist clear. It is the case of the heavenly bodies: the planets revolving around the sun, the satellites around the planets. Why does not the moon fall onto the earth and the earth fall into the sun? Newton's laws of motion

tell the answer. The antagonist is *motion*—or, to speak more precisely, momentum—or, to speak yet more precisely, angular momentum. If two particles attract one another but are moving with a relative motion which is not along the line that joins them, they never will meet. However great the attraction between them, it cannot draw them together. Attraction can do no more than constrain them to swing in permanent orbits around their common centre of mass. Therefore,

The celestial bodies exhibit to us a system kept stable by the attraction of gravity, with motion for the antagonist thereto.

However natural this statement may now seem, it is by no means an idea inborn in the human mind. There was an era when it was believed that motion dies out of itself, unless continually sustained by a never-ceasing stimulus. Were motion to die out of itself, it could not be an eternal antagonist to gravity. Newton cleared the way for the new idea by abolishing the old one.

May we now assume that the ultimate particles of the world act on each other by gravity alone, with motion as the sole antagonist to keep the universe from gathering into a single clump?

The answer to this question is a forthright and irrevocable NO.

That the answer should be *no* is not at all surprising to this generation, which is familiar with other forces than gravity, the electromagnetic forces especially. Those who underrate the prowess of our forerunners may feel surprise on hearing that the negative answer was quite as apparent to Newton. No apology is ever needed for quoting verbatim what Newton wrote in English, though it is a dangerous act for the quoter, whose writing must suffer by contrast with the simple elegance of the seventeenth century. Incurring the danger, I cite from the *Opticks* (a book of which the name falls decidedly short of the scope):

"The attractions of gravity, magnetism and electricity reach to very sensible distances, and so have been observed by vulgar eyes, and there may be others which reach to so small distances as hitherto escape observation. . . . The parts of all homogeneal hard bodies which fully touch one another stick together very strongly. And for explaining how this may be, some have invented hooked atoms, which is begging the question; and others tell us that bodies are glued together by rest, that is, by an occult quality, or rather by nothing; and others, that they stick together by conspiring motions, that is, by relative rest among themselves[1]. I had rather infer from their cohesion, that their particles attract one another by some force, which in immediate contact is exceedingly strong, at small distances per-

[1] These remarks seem to be aimed at Lucretius, or else at the Greeks from whom Lucretius took some of his ideas.

forms chemical operations, and reacbes not far from the particles witb any sensible effect."

Further along in the *Opticks* we read:

"Thus Nature will be very conformable to herself and very simple, performing all the great motions of the heavenly bodies by the attraction of gravity whicb intercedes those bodies, and almost all the small ones of their particles by some other attractive and repelling powers wbich intercede tbe particles."

With tbe powerful aid of Newton we have now distinguisbed between the attractive force of gravity and anotber attractive force, for whicb I retain the old-fashioned name "cohesion". I give anotber basis of distinction, one which could not have been found until in tbe mid-nineteentb century the equivalence of beat with mechanical work was establisbed. Consider a piece of solid or liquid matter, and put tbe question: bow much work must be done to tear its atoms apart and dissipate them into the infinite reaches of space, if the only force whereby they act on one anotber is the attraction of gravity? The question is answerable, if it is known bow massive the atoms are and how far apart (on the average) they are. These things are known. The result of the computation is to be compared with the amount of work which is actually expended—in the form of heat—wben the solid or liquid is volatilized into vapor. It is found that only about the billionth part of a millionth part of the heat so spent is devoted to "breaking down the gravitational bond", to doing work against the attraction of gravity which is overcome when the atoms are dispersed[2]. All the rest is required for overcoming that more intimate force of cohesion.

Gravity now is pusbed into the background, and sinks into the relative insignificance which may be gauged from the fact tbat in tbe endless speculations of physicists and chemists as to how matter is built up and joined together, it is completely left out. The force whicb dominates the planets, which makes a hill so hard to climb and a beigbt so dangerous to fall from—how amazing that it should be trivial, compared with others whicb the flame of the gas-jet vanquishes as the water boils out of the kettle! Trivial of course by comparison only, and at small distances, not at great; or to phrase the situation better, it is the force of cohesion which is trivial at great distances, gigantic at small. This is tbe contrast wbich is implied by the technical terms of physics, "long-range forces" versus "sbort-range forces".

[2] The computation for mercury was made by my colleague Dr. L. A. MacColl, on the basis most favorable to gravity: by assuming mercury to be a continuum, or in other words, to be made up of infinitesimal atoms infinitely close together—an assumption giving tbe greatest possible value to the work required for spreading the mercury through infinite space, if gravity be the only restraint. The latent heat of vaporization of mercury is found by experiment to be $1.88.10^{16}$ times this value. Tbus the contrast mentioned in the text is not contingent upon knowledge of the mass and spacing of the atoms, thougb the knowledge is available if wanted.

Gravity is long-range, because it falls away gently with increase of distance; cohesion is short-range, because it falls away precipitately. We shall soon be meeting with other examples of either character.

One other fact to illustrate the short-range quality of the cohesive forces: When a kettle of water is boiling away on the stove, the amount of heat consumed in dispersing the first cubic inch that departs is the same as is spent in dispersing the second, and the third, and each of the others down to and including the last. This could not be so, if the particles were drawn together by important long-range forces; for then each cubic inch would be easier to drive off than that which last preceded it into the vaporous state, since there would be less of the liquid remaining behind to attract it.

The celestial bodies—useful as they have heen in showing us the laws of motion—have therefore served us badly by hinting that gravity is the sole attractive force, a hint which is quite misleading. In another important respect they fail to give us a lead: they show us no examples of collision. Collision, more commonly known as impact, is one of the most important of earthly phenomena, as it is one of the most uncomfortable. The apple which fell in the orchard of Newton, and inspired him with the law of gravitation, may have been a legendary apple; if it was real, we may be sure that it ended its fall in a collision—ended its fall, not its existence. It did not pass through the globe and pop out of the ground in the Antipodes; it did not instantly merge with the grass or the soil of the orchard; it bounced and rolled a little, perhaps, and then lay quietly pressing against the earth, entire and whole. The earth was impenetrable to the apple, as the apple to the earth.

We do not even have to look to impact, to be taught this lesson about the impenetrable. Not less impressive than the fact that the piece of iron sticks together, is the fact that it does not shrink. For any particular choice of temperature and pressure, it has a particular volume which is its own. Work or heat must be expended to dilate it or tear it apart altogether, but also work must be expended to make it denser.

Having ascribed to attractive forces the fact that it takes heat—or let me say henceforward, energy—to vaporize a piece of matter solid or liquid, we now ascribe to repulsive forces the fact that it takes energy to squeeze the piece. The forces must be short-range—still more short-range than are the cohesive forces, inasmuch as these come into play to capture the atoms and hold them together, before those get their opportunity of crying "hold, enough!" They must be very potent, for the most terrific pressures which have been achieved by man do not avail to squeeze the most compressible solid into half of its original volume. Why talk of artificial pressures? everywhere in the globe of the earth, except within a hundred miles of the

surface, the pressure is greater hy far than any of them; and yet, the average density of the earth is less than double that of its superficial crust.

We have imagined that as two atoms approach each other, the gravitational force hetween them rises gently, the cohesive force remaining undetectahle till they come very close together, when at some critical distance it begins a sharp and sudden rise which quickly carries its value far over that of gravity. Now we are to conceive of yet a third force, repulsive, undetectable till they come still closer together, tben at a lesser critical distance entering on a sharper more sudden rise which rapidly carries its value far over those of hoth of the other two.

This essential and powerful force has no name of its own. This is hecause it is usually describhed in words not conveying directly the notion of force. What we have now encountered is the concept of the incompressihle atom, the particle of irreducihle volume—the doctrine that the atoms are to he pictured not as infinitely small like the points of geometry, hut as hard impenetrable elastic pellets, minute indeed but not inconceivably so. This is a doctrine frankly expressed hy many a thinker of the past, who perhaps was more unwilling than we to receive uncritically that difficult dogma of the point of infinite smallness. Hearken again to Newton: "It seems probahle to me that God in the beginning formed matter in solid, hard, massy, impenetrahle, moveable particles . . . incomparahly harder than any porous bodies compounded of them; even so very hard, as never to wear or hreak in pieces; no ordinary power heing able to divide what God himself made one in the first creation."

Tbe completely unsqueezahle atom corresponds to a force of repulsion which passes suddenly from zero to an infinite strength at a certain critical distance. The critical distance is the "radius of the atom." Reversely tbe idea of a force of repulsion rising rapidly indeed, hut always continuously, as two particles draw nearer—this corresponds to a squeezahle atom, witbout a definite radius. Solids and liquids in hulk are compressihle, and this seems to rule out the former idea, which anyhow is more drastic than one likes to accept. It is not ruled entirely out, for there may he interstices among the particles, and the shrinkage entailed hy pressure may he ascrihed to the atoms so setting themselves that the cavities lessen in size. However, this does not seem adequate, and it is hetter to accept a compressihle atom and make it share with the cavities the responsihility for the shrinkage. Then there is also the fact that solids expand when warmed. This is ascrihed to the atoms dancing around with the heat, and so we approach a new situation in which repulsion and motion are allied as the two antagonists to cohesion.

Instead of exploring this situation further, let us ask whether there is a difference between the concept of the more-or-less squeezahle atom and that

of the force-field curiously devised which I have been describing? Formally, there is not. But in respect of the path wbicb the mind next tries to follow, there is a difference, and a great one.

The compressible atom being accepted, one asks, of what is it made? and finds that one is thinking of a continuous substance, elastic and dense. One who is trying to become a thoroughgoing atomist is hardly pleased to discover a continuum at the base of the theory. The displeasure would not be long-lasting, if hy assigning a few simple qualities to the continuum one could arrive at the right numerical values for things that can be measured—if one could infer, for instance, that the continuum hy its nature divides itself into globules of just the same radii as the structure of crystals demands for the atoms. We are to meet in nuclear physics with a calculation singularly like this—but in general, the feat has not been done. It is not an adequate retort to say that the tboroughgoing atomist is obliged to assign to his atoms the sizes and tbe masses which they actually have, without giving any deeper reason. He manages to avoid the question; it becomes imperious, when the continuum is brought upon the scene. The road to success may lie by way of the continuum, but it is a road that has not been successfully trodden.

The force-field around the point-particle being accepted, one asks, why this so curious force-field? An inverse-square field would seem so natural as not even to ask for further explanation (but this is probably because the human mind has had two and a half centuries for getting accustomed to it). This combination of a short-range attraction with a repulsion still shorter in range cries out from explanation. Could one but somehow reduce it all to inverse-square forces, one would be more contented. This road seems impassable, but already it has been trodden—built and trodden—to splendid successes. Therefore I lay aside tbe compressible atom scooped out of a continuum, mentioning that even now we have not beard the last of it. Two stages of preparation are now required.

First, I must take more care henceforward in using the words "atom" and "particle". Hitherto I have used them interchangeably; from this moment on, "atom" is to have one meaning and "particle" another. Of the two, it will be "atom" which comes the closer to meaning what both words have meant up to now. Atom will attract atom hy the force of cohesion; atom will repel atom hy the nameless short-range force. The atoms in their turn will be made up of more elementary particles, bearing such names as "nucleus" and "electron". As to the forces between them,—that is the topic to which we are coming.

Second, I must introduce at long last the forces which the reader has so long been missing from this discourse: the electromagnetic.

Of these, it is the "electrostatic" force which stationary charges exert on

one another which concerns us the most. Newton spoke of it in one of the passages which I have just been citing, but the pleasure was denied him of knowing how it resembles gravity. Both follow the law of the inverse-square; yet two centuries were to elapse between the years when Newton proved this for the one and Coulomb for the other. The electrostatic force is broader though than gravity, for it includes an attraction and a repulsion. There are two categories of charge, the positive and the negative: any charge repels those of its own category, attracts those of the other.

This entry upon the scene of a long-range repulsion modifies the prospects of a successful picture of the world as a congeries of particles, and seems at first glance to brighten them greatly. Dismiss gravity—forget about cohesion—put the question: in an imaginary universe made up of electrified particles some positive and some negative, acting on one another by electrostatic forces only, is it possible to have stability with all of the particles standing still?

Again the answer is no. This is not, however, too disappointing: we are accustomed to motion as the antagonist of gravity in the celestial case; shall we not now introduce it to be an ally to the electrostatic repulsion, the two of them conjointly being the antagonists of the attraction?

Now with real surprise and disappointment, one stands confronted again by the ruthless negative answer. The past revives: I have said that a pre-Newtonian philosopher would scarcely have accepted motion as the deathless antagonist to gravity, because he would have helieved that motion dies out of itself. Well, the motion of an electrified particle *does* die out of itself—so says the electromagnetic theory. A proviso must here he inserted for correctness' sake, though it does not alter the situation. Uniform motion does not tend to die out—but uniform motion is useless to our amhitions. The orbital motion of a planet, the swing of a pendulum,—on these the theory must be built; but these are accelerated motions; and accelerated motions destroy themselves, when the moving body is electrified. Their energy passes into light, and the body sinks to rest. Aristotle was avenged in the nineteenth century on those who sneered at him; for what he had helieved of motion generally, was in effect what they believed of the motion of electricity. Still, as nearly everyone knows, there is, after all, an electrical theory of matter; the elementary particles are deemed to be electrified, and the forces between them are deemed to be electromagnetic.

How is all this to be reconciled? By a statement which is the prelude to the final one—provided, that is, that all works out as well as physicists now hope, and provided also that we avert our eyes from the phenomena called "nuclear". Having imagined the elementary particles as points possessed of mass and bearing charges, and acting upon one another by electromag-

netic forces, we are to treat their motions by the method of quantum mechanics, and not by the method of classic mechanics.

I will not pretend that this is a slight innovation, nor try to represent it as anything less than a great and difficult revolution in some of our most cherished habits of thought. Concepts formerly sharp, even those of position and motion themselves, become hazy; there are pitfalls and labyrinths; the mathematical technique is novel and hard. Yet in the picture of the universe as now presented, there are particles possessed of charge and mass; there are electromagnetic forces between the particles; there is motion of the particles; there is radiation, which it is just barely permissible to disregard in an outline like this one, and which I am disregarding; and outside of the realm of "nuclear" phenomena, there is nothing else. The stability of the world, that is to say, of the picture, is assured by attractions and repulsions electrical in nature, and by motion, with radiation playing an essential part.

The hydrogen atom appears before the eye of the mind as a system of a nucleus and an electron: two particles of known, equal and opposite charges, of known unequal masses, attracting one another by electrostatic force. The force draws them together, but there is kinetic energy and there is motion, and so they stay apart. It takes a definite amount of energy to separate them, and the theory derives its actual value very exactly from a basic principle. Any other atom appears before the mind as a system of a nucleus and two or more electrons. The nucleus bears a positive charge, the electrons are negative; the nucleus attracts the electrons, but they repel one another; there is motion; between the attraction and the motion and the repulsion, there is stability. A molecule is a system of two or more nuclei positively charged and two or more electrons negatively charged, and the same three qualities hold the balance. A tangible piece of metal is an enormous multitude of nuclei and electrons, these latter enjoying a very wide variety of motions, some moving almost as freely as though the metal were a vacuum: again the balance is held, the metal tending neither to shrink nor to explode.

All this is a programme for the explanation of Nature; and it is a programme which has been largely fulfilled—wherefore this lecture and a portion of the course. Not everything has been explained, nor ever will be. Quite apart from the phenomena called nuclear, there are countless things and happenings on earth which are so complicated, that they may well obey our fundamental laws without ever giving us the chance to prove it. If we should apply our assumptions to them and start to work out the consequences, it would take a geological era to finish the job. Perhaps all phenomena of life are of this type. The most that can be asked for is, that the theory should deal capably with all the phenomena for which it cannot

reasonably be claimed that tbey are so complex as to defy any theory. I do not allege that our theory of massive particles, electromagnetic forces and quantum mechanics has done even tbis. It has, however, done a great deal, so much that it takes a rather skeptical physicist to deny it in the realms to which it lays claim.

In tbe ligbt of this theory, let us consider the situation of the several forces.

Gravity remains apart and inaccessible, one of tbe ultimate forces, quite probably a quality of space as Einstein has proposed.

The *electromagnetic forces* remain ultimate, not explained in terms of anything else, united among themselves by the theory of relativity, responsible for tbe incessant passage of energy to and fro between matter and ligbt wbicb is one of the major features of the world. The ionization of atoms, the generation and the absorption of ligbt, show us tbese forces at work within tbe atoms, bolding together the electrified particles of which the atoms are made, balanced by motion and by tbeir own dual character of attractions and repulsions.

Cohesion, and the chemical forces whicb bind atoms into molecules and grade insensibly into cohesion, and tbe nameless *repulsive* force wbicb holds the balance to tbem and led many to the concept of tbe more-or-less-compressible atom: these are derivable from the electromagnetic forces between the elementary particles whereof the atoms are made up. I repeat: *derivable from the electromagnetic forces, with the aid of quantum mechanics*,—without which aid they would not have been derived. In the literature one finds incessant reference to "exchange forces"; these are not a novel category, but a step in the derivation.[3] Here are the fields of researcb where work is the most active. The theory of chemical forces, wbicb some call "quantum chemistry", is well advanced; the theory of metals, not so well. Much earlier and mucb more often than we like, do we impinge on the class of phenomena, for which it can all too reasonably be claimed that they are so complex as to defy the theorist probably for all time. Yet there are many simple ones which have brilliantly been explained, and there is satisfaction on the whole—until one raises the eyes and looks abead: for the nuclear phenomena are still before us.

As a prelude to tbese we may view the electron itself. Hardly have we begun to "look narrowly" upon it, before we see tbe spectre rising up of that old antithesis between the point-atom and tbe atom carven out of a continuum; nor is it long before the spectre grows more frightful than it was in the earlier case. If the point-electron is adopted, all the old conceptual

[3] There is also a strange quality of Nature bearing in quantum-mechanics the name of "the exclusion-principle of Pauli," which to some extent resembles a repulsive force acting between similar particles such as electron and electron or proton and proton, under very special conditions.

troubles return in the company of a new one. The intrinsic energy of this point-particle is infinite—so says the electromagnetic theory; the mass must therefore be infinite—so says the relation of Einstein of which I will presently show the power. If from this alternative we rebound to that of a globule of continuous electrical fluid, the old difficulties come back in the company of another new one. The parts of the globule of negative electricity repel each other, so our electron-model turns out to be a high-explosive bomb. The reader if he wishes may seek in Lorentz' "Theory of Electrons", a classic of some thirty years ago, the details of a scheme for preventing the electron from exploding by means of nonelectrical forces—a surrender, therefore, of the viewpoint that the ultimate forces are electrical.

Leaving these difficulties still unmastered, I turn to nuclear physics. This is a term which covers two fields: on the one hand, the structure and the qualities of atom-nuclei; on the other, some remarkable attributes of electrons, which they display either when they have tremendous energies, or under conditions which it takes tremendous energies to create. "Tremendous" energies are enjoyed by electrons fresh from radioactive substances, are obtained from the cyclotron and the electrostatic generator, and are found at their extremest in the cosmic rays. Of these attributes the only one which I will mention is mortality.

Mortality: this is a very obnoxious attribute for an elementary particle. All atomists heretofore have devised their atoms specifically to be immortal, to be *the* immortal things, to be the one thing permanently changeless under the flux of phenomena. But the electron is mortal, subject to birth and to death. Electrons are born in pairs, a positive and a negative springing together into existence. Electrons die in pairs, a positive uniting with a negative and the two of them passing out of existence.

These are not exactly cases of something coming out of nothing and something turning into nothing. Energy, mass and momentum are all conserved. Corpuscles of light disappear where and when an electron-pair is born, are born where and when a pair of electrons vanishes. So far as can be told, the corpuscles of light possess just the energy, just the mass and just the momentum which is destined to go to the nascent electrons or to be left unpossessed by those about to die. Now I have to admit my fault in not elevating earlier the corpuscles of light to a parity with the electrons and the atoms. They have the singular attribute of moving always with the same speed (when in a vacuum); they do not collide with one another, or rather such collisions have not been detected, though collisions with electrons are known; and they suffer from mortality, very much more so than do electrons. (Positive electrons are so rare, that negative electrons enjoy an almost perfect security.) Immortality is reserved for energy and mass and momentum. Now we feel ourselves swerv-

ing again toward a continuum-theory. The ground is slippery, and I step hastily from it into the last section of this lecture, into nuclear physics proper.

All of the theory of nuclei is firmly grounded on one basic statement, which is this: the masses of all nuclei are *nearly* integer multiples of a common unit, this being *slightly less than* the mass of the lightest among them.

Here is a statement bitterly disappointing! the little word "nearly" and the three little words "slightly less than" conjointly make a bright hope stillborn. Were it not for those words, we should already have joyously leaped to the conclusion that all nuclei are clusters of a single kind of fundamental particle, different clusters differing only in how many of the particles they comprise. The conclusion is so tempting that one is quite unable to resist it, hoping against hope that the words of frustration can somehow or other be cancelled. Soothing the reader with this veiled assurance, I adopt the conclusion.

The conclusion itself must be tempered at once, for there is a second basic statement coequal with the first: the charges of all nuclei are integer multiples of a common unit of charge. No pernicious adverbs here! this statement is an exact one, to the best of our knowledge and belief. The common unit of charge, as nearly everyone knows, is equal to the electron-charge and positive in sign.

The conclusion would still be sound, if the charges of all nuclei were proportionate to their masses (we should merely attribute an equal charge to every particle). Definitely this is not so, being most strikingly denied by the fact of "isobars": there are nucleus-types agreeing in mass, disagreeing in charge. We seek the next simplest assumption, and find that it suffices: Two types of fundamental particles—equal in mass—the one of them charged positively, the other neutral—each nucleus to be distinguished by two integers, one being the number of the charged component particles of the cluster, the other the number of the neutrals—"proton" and "neutron" for the names of the two.

This is the beginning of the programme for nuclear theory. Having taken the first step by writing it down, we enter upon the second—and find ourselves on the very road which our ancestors trod when atomic theory was new, facing the same ascents, the same passes and the same morasses. The long-range forces—the short-range forces—the cohesion—the repulsion—the more-or-less-incompressible particle—the troubles of the concept of the point-particle—the countervailing troubles of the continuum carven into globules—the dream of reducing everything to long-range forces and motion holding each other in balance—every one of these rejoins us on our journey. The mighty difference is, that the road still ends in the darkness, and the dream is still a dream. Therefore it is that the language of nuclear

theorists wanders about in the most disconcerting way, so that often in a single article the wording in one place will be intelligible only to a few hundred (if so many) of the most advanced of specialists, and in another will sound like the voice of Newton speaking out of the *Opticks*, only in a much more cumbrous manner.

In the atomic world we have already seen how gravitation is neglected, being pushed into the background by the electromagnetic forces and the cohesions and repulsions derivable from these. Now in their turn the electromagnetic forces must recede into the background. This sounds extraordinary. Have we not all been told of the supreme importance of nuclear charges? Have we not been taught that by its charge a nucleus attracts electrons and organizes them into a family about itself and so creates an atom,—an atom which coheres with others, so that the world as we know it is organized by the charges of nuclei? All this is true, and very important from our viewpoint—but not so important, it seems, from the viewpoint of a nucleus. To this little cluster of protons and neutrons, the mass is more important than the charge; the total number of its component particles is more important than the number of protons separately or the number of neutrons separately; the cohesive forces are more important than the electrical. Perhaps a nucleus cares little about its charge, and nothing at all about the swarm of electrons which that charge coerces to swirl about it like a cloud of flies, though if it were not for those swirls the world would be barren and dead.

The cohesive forces certainly overpower the electrical. We are in no doubt of this, for the electrical forces are repulsive. Newton had gravity available for binding his atoms together; it was of the right type but inadequate, so he gave it cohesion as an ally. The electrostatic force between proton and proton is a repulsion, so to bind such particles together the Newtons of nuclear physics must overcome it with cohesion as an adversary. How greatly it is overcome is shown in much the same sort of way, as I followed when invoking the vaporization of solids to show how greatly the cohesion of atom with atom surpasses gravity. It is possible (at the end I will mention how) to compare the amount of energy required for tearing apart a cluster of two protons and a neutron with that required for tearing apart a cluster of two neutrons and one proton. The two amounts differ by only a few per cent; and more surprising yet, the former is the greater! Though the first-named of the clusters contains the inherent explosive power of two protons trying to drive themselves apart by the long-range repulsion, it is stuck tighter together than the other, which contains nothing of the sort. As a minor detail this shows that the cohesive forces depend to some extent on whether the particles are neutrons or protons; but the major conclusion is, that the cohesive forces are the masters.

Are they short-range or long-range? By calling them "cohesive" I have already committed myself, but correctly. There is an argument quite similar to the second which I drew from the vaporization of liquids. Think again of the kettle of water boiling away on the stove. It takes as much energy from the flame to disperse the last cubic inch of water that goes as it does to drive off the first, despite the fact that the first is exposed to all the long-range forces of attraction exerted on it by all the other cubic inches remaining in the kettle, and the last is not. Therefore the long-range forces which act between atom and atom are trivial, and cohesion is a force exerted by the atoms on their near neighbors only. Think now of the cluster of protons and neutrons which is a nucleus—a massive one by choice, built of two hundred particles or more. Imagine it taken to pieces by detaching one particle after another. I admit that this precise experiment is beyond the art of the physicist, but for a certain reason—the one which I have already promised to give, and will give at the end—he is as confident of its result, as he ever is of the result of any experiment which he has not actually performed. The result is, that it takes *roughly* as much energy to remove a particle when there are two hundred left behind to pull it back, as when there are but a dozen left behind, or any number in between. Therefore the long-range forces which act between the fundamental particles are minor, and the intra-nuclear cohesion is a short-range force.

I have carefully made these last statements rather weaker than their analogues for the water boiling away. The amount of energy required for taking away a particle does depend to some extent on the number left behind, and the long-range forces are therefore minor but not trivial. If the long-range forces are attractive, the binding-energy of a particle—this is the shorter name which is given to the "energy required for taking away a particle"[4]—must be greater, the greater the size of the cluster, *i.e.*, the greater the mass of the nucleus. Now for nuclei of some fifty particles or more, the contrary is the case. Therefore the long-range force, or the major one if there are more than one, is a repulsion. We already know of one long-range repulsion, to wit, the electrostatic force between proton and proton. Is this the force in question? The answer is oddly difficult to give with assurance, but at present is believed to be *yes*.

If the answer is definitely *yes*, then the electrostatic force has after all one role of supreme importance in nuclei. It fixes their maximum size and their maximum charge, therefore limits the number of chemical elements, and may indeed be all that prevents the universe from caving together into a single lump of protons and neutrons with the electrons fluttering help-

[4] It ought strictly to be called the "unbinding-energy" or "binding lack-of-energy," since it is given as positive when energy must be contributed to the system in order to detach the particle.

lessly around it. So long have the chemists been on the search for new elements, and so completely have they searched, that we may believe them when they say that apart from the works of the "atom-smashers," no nucleus exists having more than 238 particles altogether, 92 of which are protons. Even the atom-smashers or (as I should rather call them) the transmuters, for all the wonder and power of their art, have not forced the total numher of protons upward by more than two or the total number of particles altogether upward by more than one. Moreover all of the two dozen or so most massive nuclei known are subject to explosion—to explosions quite terrific, some of them spontaneous, others touched off by what seems a very minor cause. It may therefore he taken as nearly certain that tbere is an upper limit to tbe size of nuclei, and probable that it is electrostatic force that sets the limit.

Now we come down to the short-range repulsion. Such a one tbere must he, for again we can rehearse the ancient argument. A piece of iron does not shrink into a point; tberefore the iron atoms must eitber exert a force of repulsion or else be more-or-less compressible pellets. A nucleus does not shrink into a point, but offers an impenetrahle front, measurable thougb small, to an oncoming neutron; tberefore the nuclear particles—but why repeat the words?

Shall we interpret neutrons and protons alike as systems of particles still smaller, acting on one another by electromagnetic forces, to he treated hy quantum mechanics? Alas, if there is one surety in this field, it is that we cannot play quite the same game twice. Quantum mechanics may not be used up (some think that it is) hut the electromagnetic forces certainly are. In this direction we have as yet no leadership.

Shall we then adopt the compressible globule or the point-particle witb a curious field of force surrounding it? Though the language of nuclear theorists verges sometimes on the former, it is tbe latter practice which is common—a fact which will hardly surprise the reader. In the specialized literature, one finds many a speculation and (what is of more moment) many an inference about the force-field whicb is drawn pretty directly from reliahle data. As a rule the inferences are expressed in language very different from the phrases of this lecture: "interaction" is used instead of "force-field," and there are queer and slightly comic technical terms such as "potential-well." When you read of a "rectangular potential-well," interpret that what I have heen calling the "cohesive force" becomes suddenly enormous at a certain specific radius; when of an "error-well" (!) understand that the cohesive force increases rapidly according to a certain law with decline of distance; when of a "Coulomb interaction" realize that it is the inverse-square force-field of tbe electrostatic repulsion hetween proton and proton. Of these interactions I will give only two facts: first,

that the short-range attraction is confined within a very few times 10^{-13} cm of the centre of the proton or neutron, whereas the cohesive attraction of atom for atom spreads over a radius a hundred thousand times as great; second, that the three short-range attractions of proton for proton, neutron for neutron and neutron for proton are nearly the same.

Shall we adopt the force-fields as given to us hy experiment, with some plausihle assumptions added (for one cannot as yet do without them) and operate on them hy the procedures of quantum mechanics, hoping to arrive at (say) values of binding-energies compatible with the data? This is the present, or perhaps I should say the recent, programme of nuclear theory. If one reads the theoretical papers of any one year out of the last ten, one may readily get the impression that success is just around the corner. But if one reads the papers of two or more years and takes note of the rapid changes, the prospect does not look quite so rosy—nor when one overhears the conversations of the theorists themselves. I will not conduct the reader down the paths which are as yet so tortuous and hazy; it will he hetter to fill in the picture with a few of the many remaining details.

Mass was the first of properties (along with hardness) to he assigned to the elementary particles; the second was charge; to these have lately heen added angular momentum and magnetic moment. It is difficult to say when the idea of a spinning atom was first propounded (one recalls the vortices in a continuous fluid which Kelvin introduced as one of the most brilliant of all attempts to contrive a continuum and atoms as a part of it) hut easy to fix the time when the idea of the spinning electron became so definite and sharp, as to he successfully used in explaining crucial data; this was 1925. The electron, the proton and the neutron all have equal angular momentum; its amount, common to these three which at present claim most strongly the rank of *elementary* particle, is one of the universal constants. When protons and neutrons are assemhled in a nucleus, their axes of spin all point in an identical direction, though not by any means necessarily in the same sense in that direction. It is possihle for a nucleus to have zero angular momentum, through half of its particles setting themselves in the one sense and half in the other; the lightest nucleus for which this happens is the alpha-particle, composed of two protons and two neutrons. The magnetic moments of the three elementary particles are very far from equal, that of the electron heing some seven hundred times as great as that of the proton, which in turn is half again as great as that of the neutron. One of the tragedies of theoretical physics occurred in this connection. A principle of quantum mechanics had been proposed, superbly capable of serving as a hasis for most of the incomplete principles which had already so well justified themselves in atomic physics, and including among its parts the actual values of the angular momentum and

magnetic moment of the electron. Its empire would have been extended, had the ratio of the magnetic moments of proton and electron been equal to the reciprocal of the ratio of the masses of these two—actually the former ratio is too great by a factor of 2.78. This contretemps has led many to deny the title of "elementary" particle to the proton; while as for the neutron, the fact that it lacks an apparent electric charge while nevertheless displaying a magnetic moment leaves it also open to suspicion.

Few readers of these pages will be unaware that electrons are observed proceeding out of nuclei: it may well be a source of wonderment that they are denied a residence in these assemblages of protons and neutrons only. This is of course another example of the mortality of the electron. Having observed that it is subject to birth and to death, should we be deterred from supposing that it is born as it quits the nucleus from which it comes? This rhetorical question gives a false impression of the course of history. There was indeed an era when electrons were believed to inhabit nuclei, when nuclei were regarded as assemblies of protons and electrons only. It ended in 1932; but the observation of the birth and the death of electrons did not ensue for yet another year. What happened in 1932 was the discovery of the free neutron. Only when this particle had been discovered did a physicist (Heisenberg) think it worth while to begin to develop in detail the theory that the components of nuclei are protons and neutrons and no other particles but these.

Now I bring this article to a close by fulfilling my promise to speak of Einstein's relation between energy and mass, which on the one hand has been rigorously tested in the realm of nuclear physics, and on the other has extended that realm.

The relation may be worded in several ways; I will employ the shortest: *energy has mass.*

Now imagine an assemblage of particles sticking together. "Sticking together" is not the dignified phrase of a physicist; such a one would say, more abstractly but more exactly, that energy must be given the particles to take them apart. But energy has mass; therefore the mass of the assemblage must be augmented, when they are taken apart. Therefore the mass of the interconnected assembly is less than the sum of the masses of the particles when free.

Now with a single stroke this principle does away with what otherwise would have been a quite unsurmountable obstacle to the doctrine that all nuclei are made up of protons and neutrons. For "proton" and "neutron" are not merely the names of hypothetical particles whereof nuclei are made up; they are also the names of the two lightest of nuclei. These two lightest of the nuclei are so massive, that it could not possibly be said that the other nuclei are made up of them, were it not for the detraction of mass

which occurs when they are bound up together. This deficit of mass corresponds to the unbinding-energy or, badly called, the binding-energy of which I earlier spoke. The binding-energy is the amount of energy which must be supplied to the nucleus, to break it up into protons and neutrons. The deficit of mass—the difference between the actual mass of the nucleus, and the masses of all of its neutrons and protons dispersed into freedom—is related to the binding-energy by Einstein's relation.

I have said that this relation has been tested in the realm of nuclear physics, and has served also to extend that realm. The possibility of testing arises from the fact that in certain cases the physicist is able to convert a system of two nuclei into a system of two other nuclei, the masses of all four being known. This seems a somewhat pedantic way of expressing the well-known fact that in performing an act of transmutation, the physicist causes one nucleus as "projectile" to impinge upon another as "target," whereupon the two merge and two others spring apart from the scene of the merger. The masses of the two initial nuclei do not as a rule add up to the same precise sum as the masses of the two final nuclei. But if to the first pair of masses we add that of the kinetic energy of the projectile, and if the second pair is augmented by that of the kinetic energies of the final nuclei—why, then, the equation balances, and Einstein's relation is justified.

As for the extensions of the realm of nuclear physics, or let me rather say, the realm of physics generally: no fewer than three have been stressed in these few pages. First, mass could not be conserved in the birth or the death of electron-pairs, were not the energy of the electrons accompanied by its mass when it passes out of or into the form of radiant energy. Then, we should not so soon have known that the system of two protons and one neutron requires less energy to unbind it, than the system of two neutrons and one proton; this was deducible from the masses of these two nuclei, before it was attested by the discovery that the former changes spontaneously into the latter. Then, we should not have the evidence that the binding-energy of the individual particle lessens, as the number of particles remaining behind in the nucleus increases; for this is a statement derived from observations on the masses of the nuclei.

So all seems well with the model of the nucleus as a system of protons and neutrons, and the particle-theory stands triumphant. Yet notice at what a price this triumph has been bought! Of all the attributes of the fundamental atom, of the elementary particle, constancy of mass was the earliest and the most firmly accepted. The elementary particle was a bit of immutable mass, set forever apart from change. Now it turns out that when the particle adheres to another, some of its mass departs. What has departed is not perished and gone. It is known sometimes to have passed into radiant energy, sometimes into energy of motion, sometimes into that mingling of

the two which is known by the name of heat. Changelessness has ceased to be the quality of the atom, remaining that of the mass and the energy of the world as a whole. Immortality has gone from the atom back into the continuum. This is as good a place as any to step out from the incessant alternation, never yet ended and probably endless, between the particle and the continuum as the basis of thought about physics.